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Ice Jam Data Collection

Kathleen D. White and Jon E. Zufelt

March 1994

Abstract
Ice jam data collection is necessary to gain information on ice jam events, which may occur rarely and are often short-lived, but can at the same time cause large damages. An ice jam data collection program involves field data collection, review of existing hydrologic, hydraulic, meteorological, and ice records, and a search of historical records that may pertain to ice events. This report describes the development of an ice jam data collection program, the types of information to be collected, and techniques used in field ice jam data collection.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380-89a, *Standard Practice for Use of the International System of Units,* published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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March 1994

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Kathleen D. White and Jon E. Zufelt, Research Hydraulic Engineers, of the Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). The project was funded by CWIS, Work Unit 32774, *Field Monitoring of Ice Jams.*

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Ice Jam Data Collection

KATHLEEN D. WHITE AND JON E. ZUFELT

INTRODUCTION

Ice jams cause over $100 million in damages annually in the United States. To respond effectively to ice jam emergencies, something must be known about their physical characteristics. The design of mitigation and control measures can be optimized only when the properties of ice jams are known. Therefore, data on their formation, accumulation, and related effects must be collected. Ice jam data collection involves both field measurements and review of existing hydrologic, hydraulic, and meteorological records, as well as a search of historic reports relating to local ice events.

The extent of the data collection effort depends on the needs of the end user and the constraints affecting data collection. The design of ice control measures usually requires detailed information on the hydraulics, hydrology, meteorology, and physical characteristics of the site as well as historic ice information. Conversely, the verification of some numerical hydraulic models may only require information on ice jam extent and estimated thickness, assuming that the model has been calibrated for open-water conditions and that ice-covered flow and stage information exists. Longer term studies may allow for several seasons of intense data collection, but emergency response efforts generally limit data collection to only those measurements or observations deemed absolutely necessary to make an appropriate decision on how to reduce water levels or ensure public safety. The type of ice jam and safety concerns will also affect the scope of the data to be collected. In many cases, economic constraints may also affect the data collection effort.

This report describes the types of ice jam data that must be collected for a thorough study of an ice jam event and provides guidance on developing a data collection program under both ideal and constrained conditions. Background data sources, field techniques, and safety considerations in field data collection are discussed. This report is tailored for Corps of Engineers personnel, although it should also prove useful to others.

DATA COLLECTION PROGRAM DESIGN

The development of an ice jam data collection program will follow the general outline shown in Figure 1. Before beginning the data collection, the objective(s) of the program or overall study must be clearly defined since they will determine the types of data to be collected. After the objectives of the data collection program have been established, the data needed to meet those objectives can be identified and prioritized. Next, any constraints that may affect the data collection program must be considered, since they often result in modifications to the program. Once the data collection program has been modified to reflect constraints, data collection may begin. Occasionally, data analysis may reveal the need for additional types or amounts of data.

Because of the transient nature of ice jams, ice jam data collection programs must be efficiently designed. The two most important phases in the design of a data collection program are defining its objectives and identifying any constraints on it. An effectively designed program can minimize time, effort, and resources expended, while maximizing personnel safety and the amount and quality of usable data.

Define program objectives

In general, an ice jam data collection program arises because of some danger to public property or safety, such as ice jam flooding or ice accumulations that prohibit commercial river navigation. Before we decide on what data to collect, we must first define our course of action in addressing the overall problem. For example: an ice jam is causing a rise in water levels that threatens to flood residential property. The short-term program objective in this case is: How can the problem of ice jam

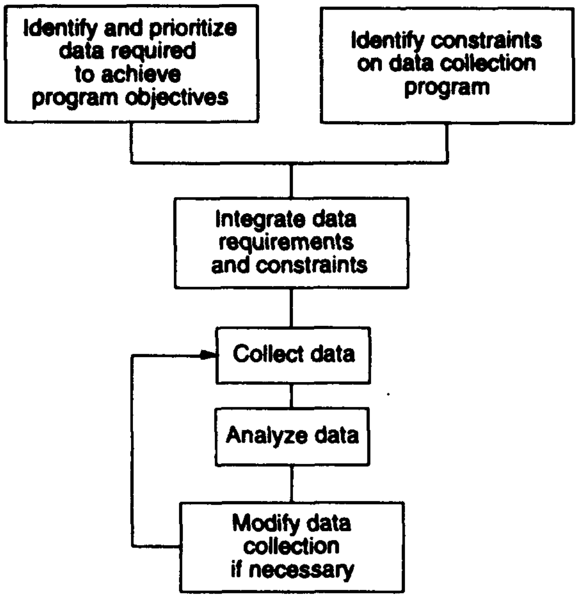


Figure 1. Elements of data collection program design.

flooding be relieved? If water levels are rising or remaining high, some course of emergency action may be warranted to lower the levels and reduce damages. A data collection program needs to be designed that will provide information on potential stages, flood areas, and flood mitigation methods as quickly as possible.

If damages from an event are more than just nuisance, an after-event assessment of damages may be necessary. The data collection program designed to meet this objective should identify flooded areas and provide detailed information on the success or failure of mitigation methods. An after-event assessment often requires rapid data collection, since changing weather may obliterate physical evidence of the jam.

If the flooding is a recurrent problem, a long-term program objective might be the development of an ice control or flood mitigation plan. The data to be collected to meet this program objective will vary with the level of detail of the study and might involve either a short-term or a long-term study process.

Ice control plans may involve the design and construction of ice control structures, the development of nonstructural flood protection schemes (i.e., flow control, thermal removal or suppression of ice covers, evacuation plans, etc.), or advance measures that are put into place only when the danger of ice jamming is imminent.

A data collection program designed to meet the needs of an ice control flood mitigation plan should identify the location and extent of the ice jam(s), the location of flooded areas, the success or failure of past ice control measures, the frequency of ice jam events, and characteristic antecedent conditions. Knowledge of both open-water and ice-affected hydraulic response to proposed measures can be obtained through numerical or physical modeling. Because ice control or flood mitigation plans are usually developed in the course of a detailed study, the level of detail of the data collection program depends on the level of analysis in the study.

Once the general course of action to be taken to address the overall problem has been identified, we can then further define our data collection program objectives. Let us discuss some typical ice jam problems and possible data collection program objectives (see Table 1).

Advance measures

If it is known that an ice jam or ice jam flooding is imminent, advance measures may be put into place that can reduce or prevent damages. Often, advance measures are considered when a midseason breakup jam occurs and freezes in place. While the jam may not have caused immediate flooding, it could pose a threat in the form of decreased channel conveyance, causing water to flow overbank during later runoff events. Or the frozen jam could provide an obstruction to further ice movement and result in additional ice jamming later in the season. Advance measures in this situation might involve the excavation of a channel within the jam (Figure 2), the removal of the jam, the construction of some type of relief channel to

Table 1. Ice jam problems and possible data collection program objectives.

Problem	*Objective*
Ice jam flood threat imminent	Advance measures
Ice jam causing present flooding	Emergency response After-event assessment following flood
Recurrent flooding	Emergency response After-event assessment Reconnaissance study Detailed study
Any of the above	Develop ice control or flood mitigation plan

a. Backhoe.

b. Dragline.

Figure 2. A flow channel through an ice jam as an advance measure or emergency response can be made using a variety of equipment (Winooski River, Vt.).

a. Prior to flooding.

b. Looking across street to the same location, after flooding.

Figure 3. Floodproofing as an advance measure to mitigate ice jam flood damage (Oil City, Pa.).

carry flow, or sandbagging to protect locations where flooding is expected (Figure 3). Advance measures can also include evacuations, emergency dike construction, thermal erosion or mechanical weakening of a jam, and any other response appropriate to the particular situation.

An ice jam data collection program should be designed to provide the information necessary to identify, and evaluate the efficacy of, advance measures. Data collected should help to answer the questions: What type of ice jam is it? What are the extent and location of the jam? How will the jam affect later water and ice discharges? How likely are further damaging water levels or discharges, and when will they occur? What areas will be damaged or flooded? and What can be done to minimize damages?

If an ice jam is already in place, its extent and location should be determined. Ice thickness and channel conveyance capacity should be measured or estimated. Downstream ice and hydraulic conditions should be documented and evaluated. The

strength of the ice and its likely response to thermal or mechanical removal methods should be assessed. Present and future water stages and damage areas should be identified. A review of historic information may give an indication of past stages or reveal the success or failure of advance or emergency response measures taken in the past. Hydrological and meteorological records, as well as past ice records, could provide information that would help evaluate the magnitude and frequency of discharge and ice events that might result in additional problems.

If there is no jam in place, but it is apparent that an ice jam is imminent, the data collection effort needs to collect information that can be used in assessing the probable location, length, and thickness of the jam. Knowledge of the upstream ice supply and of past ice jam characteristics and damage areas will be useful. The thickness, strength, and volume of ice available to form the jam, the present and predicted discharge of the river, and weather forecasts can all be used to roughly estimate the results of a jam. Knowledge of the cause of the jam could prove helpful in developing possible advance measures. For example, a competent downstream ice cover might be mechanically weakened so that it does not provide an obstruction to ice passage. Again, the success or failure of past mitigation efforts will aid in identifying the most useful advance measures.

Emergency response

The primary purpose of a data collection program during an emergency is to assess the situation and to evaluate potential emergency response measures. Data collection programs designed for an emergency situation are of necessity limited in scope. The collection of basic data allows the emergency response team to allocate personnel and supplies efficiently and effectively to minimize ice-jam-related loss of life and damage. The usual questions encountered are: How high will the water get? Which areas will be flooded? When and how far will the jam progress? How long will the jam persist? and How can we minimize the effects of the jam (or remove it altogether)?

Data collection programs for emergency situations must obtain the information necessary to determine the scope and effects of the present ice jam and the possibility of the jam growing. Estimates of the jam extent and the amount of time available before the ice jam or high water caused by the jam reaches certain locations are useful in identifying the types of emergency response measures that might be most effective. The data collected can also be used to evaluate mitigation or control methods that might be employed to relieve or minimize the effects of the ice jam. Identification of the cause(s) of the ice jam, if possible, should be addressed in the data collection program, since this will often drive the choice of mitigation methods.

An ice jam data collection program will typically include both data measured in the field and background data (existing or previously gathered field data). Fundamental field data to be collected in an emergency response situation include the location of the upstream and downstream ends of the jam and the estimated volume of ice upstream that may be available to add to the ice jam. Rough estimates of the ice jam thickness and roughness should also be made. Stages associated with the jam at different locations and times should be recorded. River ice conditions downstream from the ice jam should be documented.

Background data collection could include gathering and reviewing maps of past ice jam flood damage areas and historic flood stage data, for both open-water and ice jam events, to aid in predicting potential flood areas. Knowledge of the success or failure of past emergency response measures will help in evaluating their use in the current situation. The location and operation of hydraulic structures upstream of the jam that are capable of flow control should be ascertained. Other current information that would be helpful in decision-making are weather (temperature and precipitation) forecasts and forecasts of river conditions upstream.

Based on this knowledge, the emergency response team should be able to predict possible flood areas, the likelihood that the ice jam will progress, and the stages that could be expected under different jam progression scenarios. The potential success of mitigation or control methods can also be assessed (e.g., ice breaking, removal, melting). As with any data collection program, organized notes, figures, sketches, and photographs are very important, as this data may be useful in future studies or emergency response situations.

After-event assessment of ice jam damages

Data collected following an ice jam event is typically used to assess the level of damages incurred or the relative success of ice jam control structures or mitigation plans. Typical questions might be: How high did the water get? Which

areas were flooded? How did the ice jam form and progress? What were the antecedent conditions? How long did the jam last? and What damages occurred?

The type of data collected in an after-event assessment is primarily field data concerning the location and extent of the ice jam, areas and depth of flooding (high water marks), and other damages such as ice impact damages, erosion attributable to ice accumulations, and habitat loss. It is often useful to develop a generic ice jam data collection program well in advance of an event, which can then be quickly adapted to the specific site. It is important to inspect the damage as soon as possible following the event since much of the data (i.e., ice collars, shear walls, shore ice, high water marks, etc.) will quickly vanish with the onset of warmer weather or rain. Aerial surveys are particularly useful in after-event assessments of ice jam damages.

Reconnaissance-level studies

Reconnaissance-level studies usually arise following a damaging ice jam event in order to determine what could have been done or may be done in the future to prevent similar damages. Some questions to be addressed in a reconnaissance-level study might be: What is the extent of the ice jamming problem? What are the associated damages? Can the cause(s) be determined? and What types of mitigation measures might be appropriate? Reconnaissance-level studies are generally short term in nature and funding and thus allow for limited data collection. They are typically performed to assess the economic feasibility of a Federally sponsored project before continuing with more detailed engineering, environmental, and economic studies. A reconnaissance-level study might also be conducted for advance measures projects when time or money is constrained. Smaller problems (in terms of damages) or smaller rivers may also dictate a reduced level of study.

Reconnaissance-level data collection programs may be confined to background or archived data collection. Since the time to collect data and carry out the study is usually limited, field data collection may take place during open-water conditions. Even under optimum conditions, there will typically be only one winter of field data collection. Questions that the data collection program should address include the cause of the jam, its location and extent, areas of flooding, the frequency of jam occurrence, hydraulic and meteorological conditions leading up to the jam, and the success of any previous mitigation measures. Information on river geometry, hydraulics, and watershed characteristics should also be collected. Of particular use are reports from previous studies, after-event assessments, newspaper accounts, and other historic data.

Detailed studies

Detailed studies are often required to identify long-term solutions to ice jamming problems. These studies often take place over the course of two or more years and provide an excellent opportunity for ice jam field data collection. Detailed studies address the questions: Why do the ice jam(s) occur? How often do they occur? and What can be done to prevent or mitigate ice-related damage? Detailed studies usually culminate in the construction of a project or implementation of an ice jam mitigation plan. The ice jam data collection program for a detailed study should provide the best quality and quantity of data for a reasonable cost. The quality of the data is very important as it will ultimately determine not only the type of structure or mitigation plan but also its extent and cost.

Data collection programs designed for a detailed study usually require a much finer level of detail in hydraulic, environmental, economic, and sociological analysis than do programs designed for a reconnaissance-level study. Detailed stage–frequency, numerical and/or physical modeling, and detailed structural design analyses are typically completed for this type of study. Complete understanding and description of the ice jamming process is usually required, as are detailed ice jam stage–frequency determinations at several locations, areas of flooding, and the effects of any proposed mitigation plans. Stage–frequency determinations typically entail the development, calibration, and verification of a numerical ice-covered hydraulic model. While much data on stages, past ice jam events, and temperatures can be gathered as background data, there is usually the need for a significant amount of field data collection. Up-to-date river geometry information may be required for the development and verification of numerical models. The initiation and evolution of the ice cover over the course of the winter and its response to changing discharge and temperature is extremely important in determining the effectiveness of various ice control methods. Usually all of the field data described in the following sections are gathered during a detailed study.

Identify and prioritize data required

After the general program objective has been identified, the types of data to be collected should be listed and prioritized. It is also helpful at this point to separate the data into the two categories described above: historic or background data and data that must be obtained in the field. Keep in mind that field data previously gathered may need to be supplemented with new or additional field data of the same type. When prioritizing data, the relative importance of each item of data in meeting the data collection program objectives should be considered without respect to constraints, which will be considered at a later time.

In prioritizing the data, it is also helpful to prioritize the desired method of data collection. For example, a physical or numerical hydraulic model to analyze ice jam stages may be required for a detailed study, and thus it will be necessary to collect river geometry information. A new survey of cross-sections in the reach of interest would be the optimum choice, as this would provide up-to-date information on water depths, areas of floodplain encroachment, channel structures or modifications, and land use types. As a second choice, a previous survey of the river reach would be acceptable if it were updated in key locations. Next, using a previous survey without additional measurements might be considered. Less desirable would be spot depths, widths, and water elevations along the river. Least desirable would be widths and water surface elevations obtained from USGS or other topographic maps.

Identify program constraints

Once the program objectives are defined and the ideal data set is chosen and prioritized, constraints on the ice jam data collection program must be identified and considered. Table 2 lists some of the general constraints that should be considered for each data collection program. Because each ice jam is unique, there will be additional constraints unique to each ice jam data collection program.

Safety is the most important constraint to consider when developing an ice jam data collection program that involves collecting field data. Often, desired data such as ice thickness and water velocity cannot be measured directly without risking serious safety hazards. In such cases, either alternate means should be found to estimate such parameters, or they must be omitted from the data collection program. Safety aspects of an ice jam data collection program are discussed in greater detail below.

Time is of particular concern in an ice jam situation because the stability of the jam may change rapidly and because sudden large increases in stage are possible. In cases where data is to be collected during an ice jam, the essential information should be collected and evaluated immediately and lower priority items gathered later. Actual time spent on the surface of the ice should be minimized. The type of ice jam and the length of time that the jam has been in place may also affect the approach taken in field data collection. Freezeup jams may become stable over time, while breakup jams are often highly unstable and require extreme caution. This is by no means a rule, however, as freezeup jams can also be highly unstable.

The total amount of time available for the data collection program can be an important constraint. Under emergency conditions, the immediacy of the situation dictates that very little time is available for data collection. In addition, for after-event damage assessments, it is important to inspect the area as soon as possible following the event. Reconnaissance-level studies may not even allow time for winter-time field data collection efforts. While detailed studies usually allow for multiple winters of field data collection, there is no guarantee that an ice cover or jam will form or that conditions allowing data collection will exist during any given winter.

If the weather is too cold, field data collection becomes difficult and time-consuming. Cold weather increases safety hazards associated with field work and may necessitate the use of special equipment (e.g., snowmobiles, tents). Warm weather, on the other hand, may result in unsafe ice conditions that prohibit working on the ice surface. Darkness can also have an adverse effect on ice data collection.

Table 2. Possible constraints affecting ice jam data collection program.

Safety
Time
Weather
Economics
Personnel
Equipment
Access
Geographic Area

Available finances often dictate the number of personnel and the type of the ice data collection effort (for example, field work is more expensive than retrieving archived information). The availability and location of trained personnel may also constrain the field portion of an ice jam data collection program. Similarly, the location, condition, and availability of special equipment such as ice thickness kits or velocity probes may impact collection of field data. If the geographic area covered by an ice jam is large, a few representative or critical sites for data collection must be located ahead of time. Safety and ease of access should be considered when locating data collection sites. Aerial surveys are particularly useful when the geographic area affected by an ice jam is large, or when access to the jam is restricted.

Integrate objectives and constraints

In this phase of developing a data collection program, priorities and constraints are weighed to come up with the most efficient program that provides the highest quality data possible. Integrating objectives and constraints may affect the prioritization of data or the methods used to obtain data. It must be remembered that some constraints may not be revealed until well into the data collection program. For example, the initial plan may call for the identification of the upstream and downstream limits of an ice jam in a remote region by aerial survey. However, cloud cover, snow, or rain at the time of the jam may prevent or hinder aerial surveys. If this is a very high priority item in the data collection program, alternate methods of obtaining this information (and the associated constraints) should be considered in the initial program development.

Because ice jam data collection involves a dynamic process, the optimum data collection program should be considered as a base plan, with options for modification if necessary. Especially for emergency action data collection, several *if* ... *then* alternatives should be included. For example, *if* it is not possible to get stage measurements from a water stage gauge in the affected area, *then* set up a temporary reference (such as a sign, bridge abutment, or building) and measure stages against it. In this way, the important data will not be foregone given the occurrence of some unforeseen constraint. The different types of data to be collected vary with the objectives of the data collection program, as shown in Table 3. The general types of data and sources are described in detail in the following sections.

BACKGROUND DATA COLLECTION

While field and office-based data collection can occur concurrently in an emergency situation, it is common to begin the background data collection as early as possible, particularly since background data can be helpful in identifying specific locations for field data collection and special hazards associated with data collection. A review of the background data may also reveal important gaps in the understanding of the ice jam problem and therefore identify areas to concentrate on during field data collection.

All available information on the ice jam should be reviewed before field data collection begins, as this data is often used to identify sites for later field data collection. Background information may include data from the U.S. Army Cold Regions Research and Engineering Laboratory's Ice Jam Data Base (White and Bement 1993); discharge records from USGS or Corps of Engineers gauging stations or other sources such as hydroelectric facilities or reservoirs; temperature records from the National Weather Service; topographic mapping; flood insurance studies and mapping; HEC-2 or other hydraulic models of the river reach; technical reports such as a Corps of Engineers 205 study, flood plain information reports, or other reports that may be identified in the ice jam database; local civil defense unit reports; state emergency agency reports; newspaper accounts of ice jams; and anecdotal records of ice events by local residents.

A review of such background information should help to categorize the ice jam (i.e., freezeup or breakup) and identify the type of ice involved (e.g., frazil, ice blocks) and possibly the conditions that favor ice jam formation and breakup. The records may indicate whether ice jam control methods have been attempted in the past and the success of those attempts. Descriptions of emergency response measures and of past flood damage can be of immediate use in an emergency situation. A thorough review may aid in locating the initiation point of a jam, its estimated length, and perhaps its thickness, so as to determine the volume of ice involved in past ice jam events. This will help to identify the portion of the river basin that has contributed ice to the jam in the past, which is useful in estimating ice supply and in designing ice control measures. The effects of the ice jam on stages along the river and the extent of flooding may have been documented, as well as discharges immediately prior to the event.

Table 3. Typical ice data collection program objectives.

Purpose of data collection	*Typical data required*
Assess emergency conditions, evaluate potential advance or emergency response measures	Type of ice jam
	Locations of upstream and downstream ends of jam
	Location of present flood areas
	Location of potential flood areas
	Past flood fighting measures
	Stage data
	Ice thickness measurements
	Upstream ice supply
	Jam progression rate
	Predicted weather
	Historic stage data
After-event damage assessment	Location of flood areas
	Stage data
	Flood fighting measures
Reconnaissance-level study	Type of ice jam
	Locations of upstream and downstream ends of jam
	Ice thickness measurements
	Stage data
	Historic stage data
	Historic discharge data
	Historic ice jam records
	Jam progression rate
	Antecedent conditions (e.g., sudden rainfall event, rise or drop in air temperature)
	River geometry and hydraulics affecting jam
	Locations of flooded areas
Develop ice jam stage–frequency curve	Historic ice jam data
	Historic stage data
	Historic discharge data
	Channel geometry
	Hydraulic characteristics
Validate ice-covered hydraulic models (numerical or physical)	Verified open-water hydraulic model
	Type of ice jam
	Ice thickness measurements at selected locations
	Location of upstream and downstream ends of jam
Design ice control method or develop mitigation plan	Ice jam characteristics
	Knowledge of emergency response measures
	Ice jam stage–frequency
	Open-water numerical/physical hydraulic model
	Ice-covered numerical/physical hydraulic model

Type of ice jam

An ice jam is a stationary accumulation of ice that restricts flow. This flow restriction may result in significant increases in stage upstream from the ice jam or equally significant decreases in flow and stage downstream from the jam. More complete descriptions of ice formation and ice jam processes have been discussed by Michel (1971) and Ashton (1986), among others. For the purposes of characterizing ice jams, we generally group them into three categories: freezeup jams, breakup jams, or a combination of both. Each category involves a different approach to field data collection and ice jam mitigation and control.

Freezeup jams are associated with cold air temperatures and high frazil ice production. The frazil ice is transported along the river until it reaches a stopping point and begins to accumulate. Freezeup ice jams may be initiated by sudden changes in water slope from steep to mild, river bends, or

obstructions such as fallen trees, intact ice covers, and bridge piers. As more ice contributes to the jam, it thickens, further reducing the channel conveyance capacity and increasing upstream water levels. With continued cold weather, the ice jam can freeze in place. Freezeup jams often occur in early and midwinter, although they have been observed in late winter. A typical freezeup jam is shown in Figure 4.

Parameters important in characterizing freezeup jams include the location of frazil ice production areas, the quantity of frazil ice produced under different conditions, frazil ice transport and accumulation characteristics, ice jam toe or initiation location, ice jam extent, air temperature, river geometry, river hydraulics, discharge, and water surface slope.

Breakup jams are often associated with a rainfall event, an increase in air temperature causing snowmelt, ice strength degradation due to sunlight or warm air temperatures, or some combination of the above that results in sudden large increases in discharge, which can induce the failure of an ice cover. Rapid fluctuations in discharge resulting from peaking operations at hydroelectric plants have also been known to cause ice cover breakup. The broken ice pieces are carried downstream and can accumulate to form an ice jam in a manner similar to a freezeup jam. Breakup jams may occur throughout the winter but are most common in mid- to late winter. In some cases, a midwinter breakup ice jam freezes in place, and additional ice growth in the river can form enough ice for a second, late-season, jam. A typical breakup jam is shown in Figure 5.

Important breakup jam characteristics include the location of the jam toe, ice jam extent, ice piece thickness, volume of ice, ice accumulation characteristics, downstream ice conditions, water slope, river hydraulics, discharge, river geometry, drainage basin characteristics, antecedent snow cover depth, and air temperature and precipitation records.

Some ice jams result from a combination of freezeup and breakup conditions. For example, large frazil deposits form in a dredged area of the Allegheny River downstream from its confluence with Oil Creek at Oil City, Pennsylvania. These deposits form a thick, competent ice cover that resists breakup under conditions that do break up the ice cover on Oil Creek. Breakup jams formed by the jamming of Oil Creek ice at its confluence with the Allegheny River have caused a great deal of flood damages in Oil City. To find a solution to this problem, CRREL Ice Engineering Research Branch personnel needed to examine both the

Figure 4. Freezeup ice jam (Salmon River, Idaho). Frazil ice is being transported downstream in the open lead. Note the typical appearance of the ice jam surface.

Figure 5. Breakup ice jams are usually associated with significant increases in discharge. Note the wide distribution of ice piece sizes, from large blocks to brash (St. John River, Me.).

conditions leading to the formation of the freezeup ice cover and frazil deposits on the Allegheny River as well as the breakup conditions of Oil Creek (Deck and Gooch 1981).

River geometry

River geometry plays an important role in the formation of ice jams and in the damages associated with an ice jam. Knowledge of the river geometry can be useful in identifying possible ice jam formation sites, ice jam flooding locations, areas where potential mitigation efforts should be applied, and points for access to the river for monitoring purposes. Some important geometric characteristics to locate are abrupt changes in slope such as those that occur due to the backwater from a dam or river confluence; river bends or confluences; and weirs, dams, irrigation diversion structures, locks, bridges, and other obstructions to flow.

The base maps used to delineate open-water floods for flood insurance studies often provide quite detailed mapping along rivers (Figure 6). The hydraulic models prepared for the same studies also have detailed cross-sectional river information as well as bridge geometry, culvert geometry, and bed and overbank roughness estimates. Topographic maps, which provide geometric information over a large area, should be used in conjunction with local mapping on a larger scale. Natural floodplains that could provide ice storage may be determined from an examination of topographic maps.

River geometry parameters that may be important in ice jams include bed geometry and slope; the bottom width of the channel; the geometry of hydraulic structures such as weirs, groins, dams, bridges, and mooring areas; the locations of confluences; bed material and sediment transport potential; and overbank characteristics such as vegetation, width of floodplain, and extent of development.

Hydrology

Hydrologic analysis of ice-jam-related flooding is more complicated than for open-water floods because of the variability in the conditions that lead to ice jams. The two most basic hydrological parameters of interest are water stage and discharge. Other important parameters include the size of the drainage basin; basin characteristics such as slope, degree of forestation, and the nature of development; the number and locations of tributaries; rainfall–runoff and snowmelt–runoff relationships; and the number and locations of flood storage or other flow control facilities within the drainage basin.

Basic hydrologic measurements such as stage and discharge are often difficult to obtain during winter. Stage-measuring gauges may freeze or be otherwise affected by ice conditions in the river, yielding no data or data of questionable value. According to Melcher and Walker (1990), the stage–discharge rating curves of more than half of the 6500 streamflow gauges in the United States are affected by ice during some part of the winter. Ice effects must be taken into account when using stage data to estimate discharge. Hoyt (1913) provides a thorough and still-contemporary discussion of ice effects on discharge.

It is rare that a gauging station is located within an ice jam area, so gauge information must be examined carefully to deduce conditions before, during, and after a jam. For example, if a gauge is located downstream from an ice jam, a sudden decrease in stage or discharge may reflect the

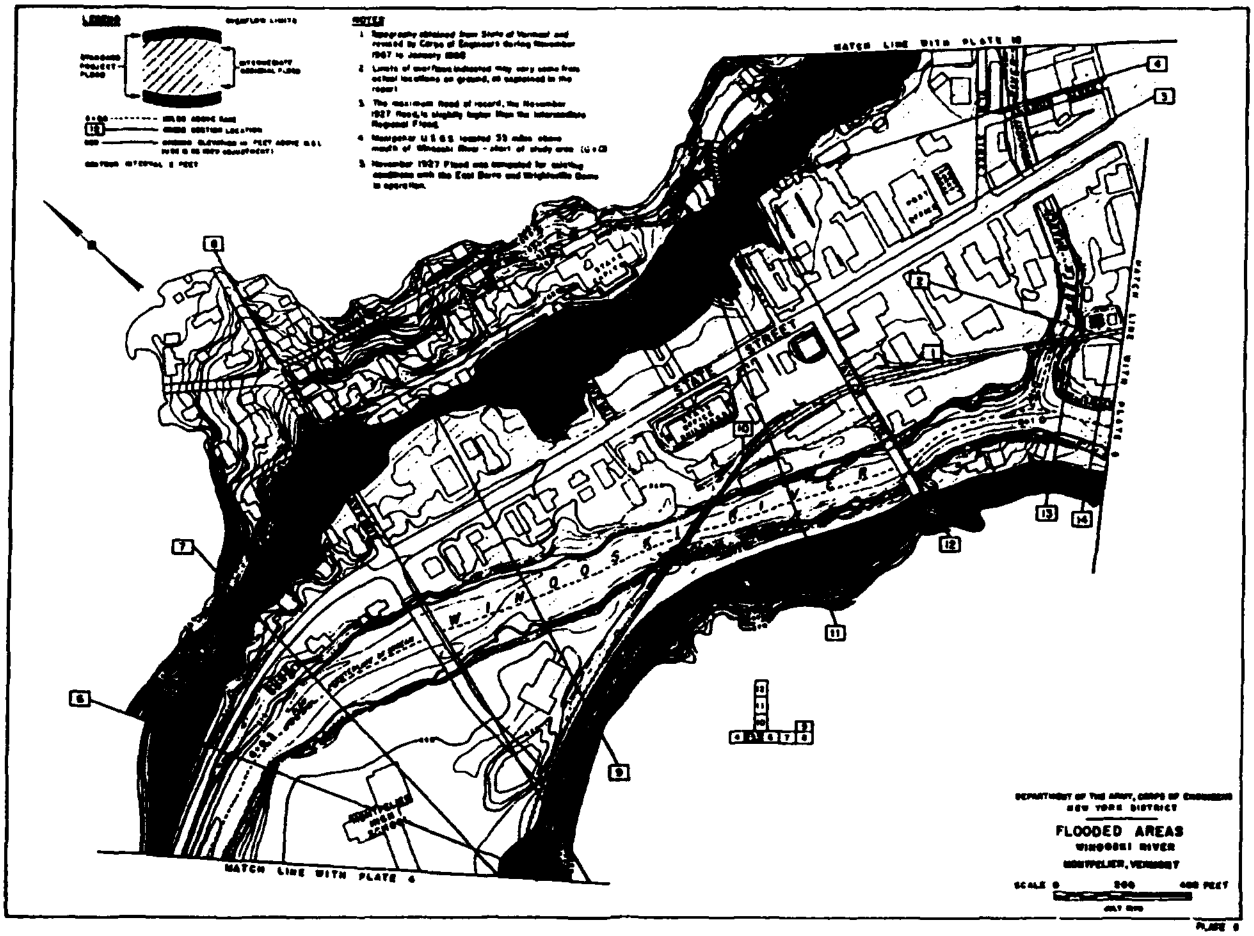


Figure 6. Flood insurance study mapping often provides very detailed maps of river corridors. This map has 60-cm (2-ft) contour intervals.

building of an ice jam upstream (Figure 7). Minimum stages reported due to freezeup can indicate large frazil ice production or the formation and progression of a freezeup jam upstream from the gauge. Frazil and anchor ice formation may also result in diurnal stage fluctuation.

A gauge located a short distance upstream from an ice jam will often exhibit backwater effects from the downstream ice jam in the form of increases in reported stage or discharge during the jam period. In this situation, an increase in stage may be incorrectly attributed to an increase in discharge, further confusing the problem. In many cases it is difficult to distinguish between increases in discharge that cause ice to break up and jam and increases in stage that are a result of a jam.

When a stream gauging station is located within an ice jam area, it can provide valuable information about stages during jam formation, first through backwater effects and then through changes in stage as the jam progresses past the gauge (Figure 8). Finally, the gauge records may indicate the time and conditions when the jam breaks up, if the gauge is not frozen or otherwise affected.

Ice-influenced flood frequency analyses may be made using gauging station data if a gauge is located in the area affected by a particular ice jam. Several methods of developing an ice-influenced frequency analysis are presented in USACE (1991).

General watershed hydrology should be reviewed. For example, knowledge of the range of elevations, average drainage area, slope, degree and nature of development, time of concentration, and lag time can all be used to predict the response of the mainstem and tributaries to a rapid snow-

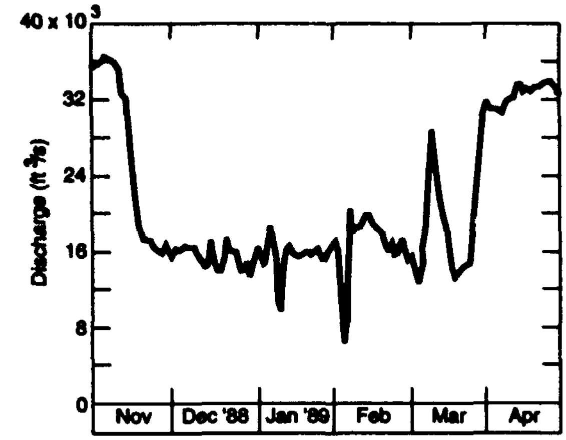


Figure 7. Frazil ice production of jamming may be reflected in gauge records as a decrease in flow. For the Missouri River at Omaha, the minimum gauge height for the period 1928–1991 occurred due to freezeup on 5 February, 1989.

melt or precipitation event. If there are any dams within the watershed, check to see if Phase I or Phase II dam safety inspection reports exist. These often contain useful hydrological and hydraulic information, as well as describing the storage capacity and dam controls available.

A range of appropriate discharges for ice-covered conditions can be developed by applying a frequency analysis to USGS gauging station records for the appropriate part of the winter. For a freezeup ice jam, early or midwinter records might be examined, while mid- to late-winter records might

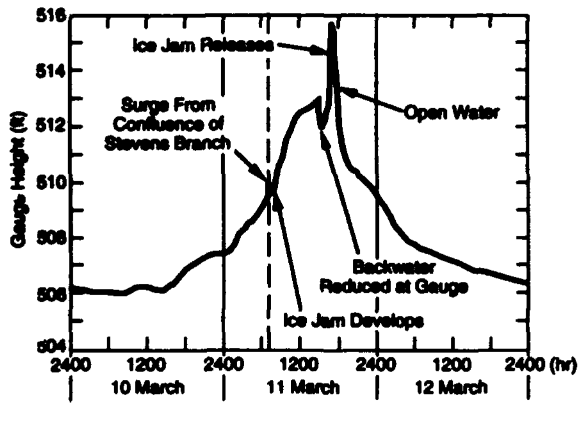


Figure 8. Valuable information about the formation and progression of an ice jam may be obtained when a gauge is located in a jam reach (after Denner and Brown, in press).

be more suitable in a breakup jam situation. USACE (1991) has developed guidance for preparing an ice-influenced frequency analysis.

Hydraulics

The location and thickness of an ice jam are controlled in large part by the river hydraulics. Important river hydraulics parameters include water surface elevation (stage), water surface and energy slope (particularly changes in slope), bed roughness, under-ice roughness, flow velocity and its distribution within the channel, likely areas of flow diversion or storage during high stages, and changes in channel conveyance.

Hydraulic models such as HEC-2 (USACE 1990a), developed for flood plain information studies or flood insurance studies, are available for many rivers in the U.S. These models generally address open-water flow conditions, although some modeling does exist for ice-covered flow conditions. These models usually contain detailed, surveyed, geometric information at selected river cross-sections. In addition, the models can provide information on bed roughness, changes in channel conveyance, possible overbank storage areas, and flow velocity and distribution under open-water conditions.

The discharge used in an ice-covered hydraulic analysis should be chosen with care. While typical hydraulic analyses are usually made using flood flow discharges (i.e., 10-, 50-, 100-, or 500-year return intervals), ice jams often occur during low flows, which may present modeling difficulties in addition to those associated with ice. For example, changes in channel conveyance may be exaggerated, or critical flow velocity may occur more often during low flows. Open-water, low-flow hydraulic models should be verified with field data where possible before attempting to model the ice-covered case. Examination of an open-water flow model prepared using a normal winter discharge may reveal changes in water slope, channel velocity, or channel width that could contribute to the formation of an ice jam.

The step-backwater computer program HEC-2, which is commonly used to predict open-water flood levels, may be used with care to examine the effects of an ice cover on river hydraulics. However, considerable engineering judgment is necessary to develop reasonable results using the HEC-2 Ice Option. Wuebben and Gagnon (in prep.) have developed a computer program that may be used in conjunction with HEC-2 to develop ice jam profiles. As with many computer models, it is

possible to obtain results that look perfectly reasonable, yet do not reflect the actual situation. Any model developed for the ice-covered case must be verified using the best field data available on ice thickness, stage, ice extent, and ice roughness.

Meteorology

Meteorological information such as temperature, precipitation, and snow depth are useful in an ice jam data collection program. Because ice growth depends on cold temperatures, ice thickness in lakes, reservoirs, and slow-moving areas of rivers can be estimated using minimum, maximum, and average air temperatures for selected locations obtained from the National Weather Service (see, for example, USACE 1990b). Freezing degree days (FDD) and accumulated freezing degree days (AFDD) are temperature statistics that are often used to estimate the relative severity of a winter season (Figure 9). Frazil ice grows in turbulent river reaches only when the air is very cold, so air temperature records may be used to estimate periods of frazil ice production. The progression of freezeup jams has been shown to rely not only on the accumulated freezing degree days in a winter season but on the severity of the subfreezing temperatures as well (Zufelt and Bilello 1992).

Knowledge of air temperature, antecedent snow depth, and snow moisture content can aid in predicting runoff due to snowmelt, which may result in breakup ice jams. Information on these parameters and on the intensity and quantity of precipitation events that might lead to or exacerbate

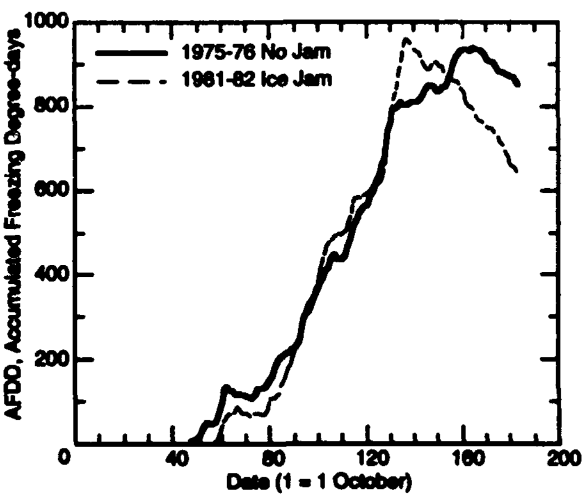


Figure 9. Accumulated freezing degree days (AFDD) are often used as a measure of the severity of a winter season.

breakup ice jams can also be obtained from the National Weather Service. In some locations, the NWS may make short-term predictions of stage during an ice jam event or will report existing stages or flood areas. During emergency situations, both short-term and long-term forecasts of temperature and precipitation should be obtained and continually updated.

SAFETY

This section is not meant to express or advocate official Corps policy, but instead presents the combined knowledge and experience of many scientists, researchers, and technicians at USA CRREL with regard to precautionary measures to be observed while gathering field data during winter or ice conditions. The information is by no means all-inclusive or meant to encompass every ice condition to be encountered, but rather presents general, common-sense precautionary measures that should be followed while conducting field measurements on ice.

While there are dangers associated with field data collection of any type, ice jam data collection has a particular set of hazards due mainly to the cold air and water temperatures usually experienced in winter, the possible instability of the ice cover, and the normal hazards encountered when working in or near moving water. During the planning phase of an ice jam data collection program, the team members should evaluate the possible safety constraints, discussed below, on their data collection program. They should also prepare an activity hazard analysis that identifies any special, additional hazards unique to the particular ice jam problem. This exercise will be extremely useful in identifying safety hazards, controls, and data collection program safety constraints for the team members.

Guidance for preparing an activity hazard analysis is given by the South Pacific Division, U.S. Army Corps of Engineers (1986). The safety hazard analysis should address the possibility of cold weather rescue. Ice rescue training, such as that sponsored by the International Association of Dive Rescue Specialists, can be of value. Methods of self-rescue and rescue by other field party members should be included in the plan. The use of harnesses, ropes, or a "throw bag" containing a floating nylon rescue rope should be considered.

The ideal time (from the researcher's standpoint) to collect physical ice jam data is immedi-

ately after an ice jam has formed. However, this is also the time when the ice is least stable. Breakup jams are notoriously unstable and can surge or fail very rapidly, either locally or over long reaches, providing very little reaction time. Freezeup jams are initially highly unstable but may develop a degree of stability with continued subfreezing air temperatures. However, open-water leads can appear rather suddenly within an apparently stable jam. Any type of ice cover should be treated with caution. The most important advice to keep in mind is this:

Do not venture onto an ice cover if there is any question at all about its stability.

This report cannot possibly cover all of the safety-related topics that a field party should be prepared to deal with. The leader of the field party should be aware of whether members of the field party can swim, the likelihood of panic in an emergency situation, and the level of physical activity each person is capable of. Physical conditions that might affect mobility and communication should be known, as well as the medical conditions of all party members, particularly diabetics, epileptics, and people who might encounter conditions that cause severe allergic reactions. Prescription drugs used by members of the data collection party should also be identified.

Cold-weather injuries and first aid are described in detail in a number of publications, including Wilkerson (1990) and U.S. Army (1976). Field-party members should be familiar with the types of cold injuries that can occur, their warning signs, and how to deal with or avoid cold injuries. Keep in mind that cold, tired people are more likely to make mistakes, decreasing the level of safety for the entire field party.

Working in the cold

The majority of ice jam data collection activities will take place during cold weather. The members of the field party should be prepared by dressing properly for adverse conditions. This is particularly important because hypothermia can occur even in relatively warm winter weather if one is not adequately dressed or nourished. Hypothermia results in diminished perceptive and reasoning capacities as well as decreased physical coordination, all of which can lead to accidents. Members of a field party exhibiting any of these characteristics are a safety hazard to themselves and the other members of the party, particularly since victims of hypothermia often do not acknowledge their symptoms and may deny them.

Frostbite can be avoided through the use of appropriate clothing and by monitoring the condition of exposed skin. Boots should provide adequate insulation, particularly in the sole and toecap. They should also be roomy, since restrictions in blood flow caused by constrictions and pressure points will inhibit warming of the extremities. Mittens are preferred to gloves for keeping fingers warm. Thin glove liners that fit beneath mittens can be worn when manual dexterity is necessary (remember not to touch cold metal with bare skin!). Fingertips, noses, cheeks, lips, and the tips of ears are susceptible to frostbite, so check them frequently, or have a partner check them. Smokers and other tobacco users are at higher risk for frostbite, as are those who have recently used alcohol or drugs, because these substances constrict blood vessels. Frostbite occurs more rapidly as the wind speed increases, so pay particular attention in windy conditions.

Dehydration often occurs in people who are working in the cold. The effects of dehydration include lethargy, headaches, and nausea. All of these effects will have an adverse impact on the safety and efficiency of both the affected person and the other members of the field party. Field-party members should be aware of dehydration and should have an ample supply of fluids to drink. Coffee, tea, and cocoa are often attractive when working in the cold, but they are all diuretics and will increase dehydration. Water and fruit juices, either warm or cold, are preferable. Liquids should be ingested before thirst sets in, in amounts 2 to 7.5 liters (2 quarts to 2 gallons) per day, depending on the level of exertion and the amount of fluids lost through respiration and perspiration. Fluid intake at the upper end of this range is appropriate in dry conditions or at altitudes above 2400 m (8000 ft) or so (Wilkerson 1990, U.S. Army 1976).

Dressing for ice jam data collection

A word about clothing is in order. Clothing is required that will keep the field party warm during varying levels of physical exertion while at the same time providing the necessary mobility. Clothes that provide good protection against the cold for land-based field data collection may not be suitable for data collection that involves travel over ice. Denner (1990) presents a thorough discussion of clothing appropriate for winter field work.

Members of a field data collection team should dress for the eventuality that the ice might fail and one of the party goes into the water. The most basic requirement is that all members of a field party who may be on the ice should be physically capable of swimming, or at least staying afloat, while fully clothed. Nonswimmers are more likely to panic and less likely to help themselves than swimmers. Hip boots or waders can be extremely dangerous and should not be worn for ice jam data collection because they restrict mobility and add weight when filled even partially with water.

Personal flotation devices, preferable Coast Guard-approved Type III PFDs, should be required for all party members (Figure 10). Even those who expect to remain on shore should be prepared for an emergency situation in which they might be exposed to the water. Flotation jackets are available that are reasonably warm and allow the flexibility of movement necessary to perform the required field work. Some jackets are lined with material that provides insulation as well as flotation, and some are lined with manually inflatable flotation cells. An alternative is an inflatable flotation vest worn as the outside layer (Figure 11). These may be either automatically or manually inflated.

Ice jam data collection usually involves short periods of intense effort followed by a great deal of time spent moving slowly, if at all. Wearing loose layers of clean, dry clothes that can be added or removed as necessary is the most efficient way to dress. Hats can prevent a significant amount of heat loss. The importance of well-insulated, roomy boots has already been described. If boots with felt liners are worn, the liners should be dried each night, as they can absorb a great deal of moisture.

Dressing in an appropriate manner can not only minimize the safety hazards associated with ice jam data collection in the field, but can also contribute to the quality of the data collected. As Hoyt (1913) points out, "The accuracy of many measurements has been much impaired by hurried work resulting from the personal discomfort of the person making the measurement" (p. 69).

Working on the ice

Minimize the actual time spent on the ice

Since an ice jam is an unstable working surface, it is best to minimize the actual time spent on the ice. A well-laid out data collection plan, familiarity with testing equipment, and good communication and teamwork are required for efficient use of time. Keep in mind that efficiency does not imply hurry: hurrying can lead to accidents.

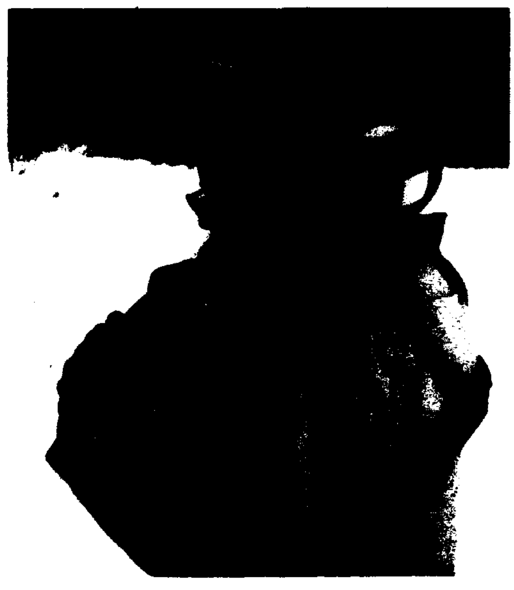
Never engage in ice data collection alone

Even if you are collecting data along the shore rather than actually on the ice, the possibility exists that you could slip and fall into the water. In remote areas, it is essential to let someone know the location and estimated time of return each day of your field party. Even in populated areas it is a

Figure 10. Personal flotation devices should be worn whenever data is being collected near the water.

a. Sleds can be used to haul equipment and provide emergency flotation.

b. This jacket has a manually inflatable inner bladder.



c. The inflatable vest on this researcher allows for freedom of movement and may be worn over bulky clothes.

Figure 11. Inflatable PFDs can provide warmth or extra freedom of movement as well as flotation.

good idea to keep others informed of your intended plans.

Always work in pairs on the ice

If there are more than two people in the field party, use the "buddy system" so that each person is responsible for another at all times. Each member of the pair should be familiar with ice rescue techniques and capable of performing them.

Monitor ice conditions

Before beginning data collection at a particular location, the local ice conditions should be surveyed visually. Are there any open leads? If so, monitor the water level and size of the lead, preferably using some kind of marker, because increases may be almost imperceptible. (If the water does start to rise, leave the ice immediately.) Listen to the ice: loud cracking noises or booms can indicate incipient failure. Before going onto the ice, choose an entry point away from hinge cracks (cracks running parallel to the shore), if possible, and one that provides easy access to the shore.

Test the ice

Each person should be equipped with a heavy, pointed iron bar that is used to test the competence of the ice. The lead person raises the iron bar and thrusts it into the ice before taking every step (Figure 12). If the pointed end of the bar goes through the ice, DO NOT PROCEED. Backtrack and choose an alternate route, continuing to test the ice strength with each step. If the water or air temperature has been above 0°C (32°F) for an appreciable length of time, the ice may be starting to deteriorate. Deterioration or thinning of ice can be quite irregular, so it is doubly important to check the ice thoroughly under these conditions.

Measure ice thickness

The thickness of the ice should be measured at intervals (see method below), but keep in mind that ice jam thickness and competence can vary considerably in a short distance. Because of this, the people following the leader should **walk only in the footsteps of the leader unless they have personally tested the ice** (Figure 13). Some distance should be kept between each person moving on the ice, to minimize loading and to reduce the chances of both people going through the ice in the event of failure. The distance will vary with different ice conditions, but 3 m (10 ft) is a good minimum.

FIELD DATA COLLECTION

After the program objectives and constraints have been identified and integrated, and after a safety hazard analysis has been prepared, field data collection can begin. As noted previously, the extent of field data collection may be limited by safety, access, equipment, financial constraints, and time, among other things.

The purpose of the field portion of the overall ice jam data collection program is to identify the physical characteristics of an ice jam and other characteristics that affect the jam. Some important physical characteristics are ice jam location and

Figure 12. Test the ice before each step, and work in pairs. Here, heavy equipment is pulled on a sled to avoid making many trips and thus minimize time spent on the ice.

Figure 13. Walk only in the footsteps of others. The snow cover over this freezeup ice jam provides a deceptive surface, covering cracks or holes. The members of the field party have made multiple trips following the same path. The researcher is using an iron bar to test the ice in an untested area.

extent, upstream ice supply, ice thickness, possible causes of the jam, and water velocity and stage. If bed or bank scour due to the presence of an ice jam is of concern, the water velocity, ice roughness, and bed morphology are of concern. Sources of information to review when selecting parameters and methods for field data collection include Beltaos (1978), Elhadi and Lockhart (1989), Beltaos et al. (1990), USACE (1991), and Pomerleau (1992a).

Recording field data

Before the actual field work begins, the method(s) of recording the data collected should be addressed. To minimize time spent on the ice, blank data sheets such as those shown in Figure 14 (Pomerleau 1992a, b) or Figure 15 (after Beltaos et al. 1990), on which pertinent data can be rapidly entered, are helpful. A surveyor's notebook with waterproof pages can prevent the loss or damage of information. Similarly, pencils are less affected by wet, cold conditions than pens. Ice jam location, jam extent, and the locations of data collection sites should be recorded on the best available maps.

Use a still camera to record conditions at the site. A wide or normal lens is adequate in most cases, but zoom lenses may also prove useful. If a battery-powered camera is used, it should be kept inside the user's outer garment when the air temperature is very cold to keep the batteries warm enough to function. As an alternative, a completely manual camera and a selenium solar cell light meter work well in all conditions. If safety permits, include your co-worker in the photo for a sense of scale. Otherwise, tapes, rules, field books, or other field equipment can be used to provide scale. Notes on the number, time, location, and the object of primary importance of each photo should be entered in a field book.

Video camera footage taken during active freezeup and breakup processes can be valuable for later analysis. Take care to set the correct date and time on the video recorder and have this information showing in the viewfinder during recording. Video taken by the news media, especially television station news crews, can often be obtained after the event.

Type of ice jam

Knowledge of the type of ice jam, whether freezeup, breakup, or a combination of both, is important in evaluating safety aspects of data collection and possible jam mitigation or control methods. Determining the type of ice jam can help determine the course of action to take in responding to the ice jam as well as in evaluating the effects of forecasted weather on the situation. The type of jam may be determined by reviewing the conditions leading to its formation and/or examining the predominant ice type. For example, an ice jam that formed early in the winter following several days of very cold temperatures is likely to be a freezeup jam. Conversely, one that formed after several days of warm temperatures or rain could be either a breakup jam or combination jam, depending on the predominant ice type.

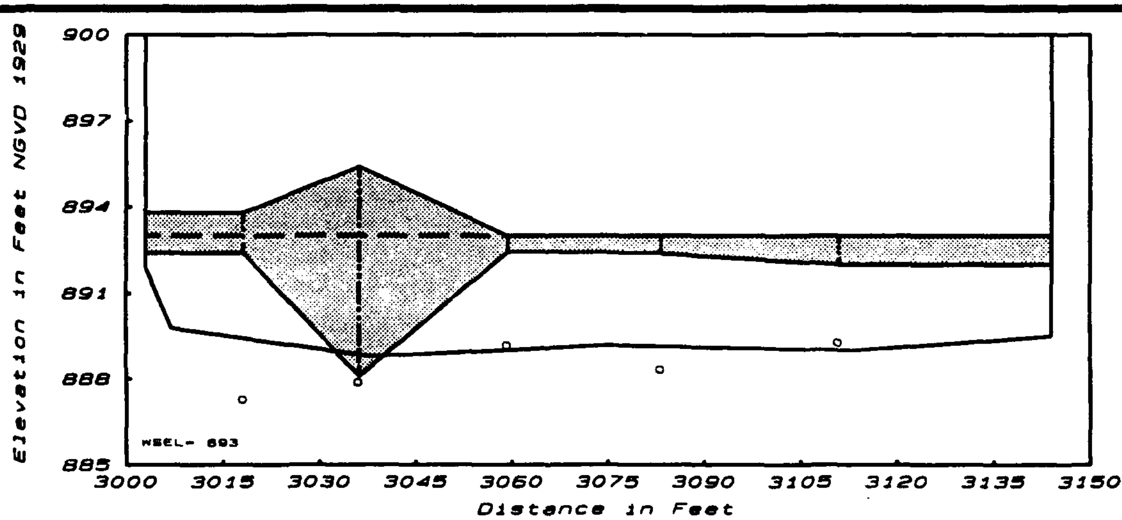
Visual examination of the ice pieces making up the jam helps to determine whether a significant amount of frazil ice is present, indicating a freezeup

Ice Engineering Field Surveys

Cannon River, Minnesota City of Northfield Downstream of City Dam	Date: 03/JA/92	Time: 10: 30	Crew: rtp mah frh	Map Key: CA-B
Reference Point Description: Second Street Bridge Center of Bridge, Top of Curb on Upstream Side	RP Elev: 908.30	Stage +/- -15.3	Ice Water X	Topwidth: 140

Measurement Type	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
Ice Thickness	1.4	7.3	0.55	0.61	1.0
Total Depth	6.4	7.4	3.7	4.55	3.6
Water Depth	5.6	5.0	3.7	4.55	3.6
Distance from Left Shoreline	15.2	33.2	56.4	80.3	108.0
Distance from Right Shoreline	124.8	106.8	83.6	59.7	32.0
Other:					

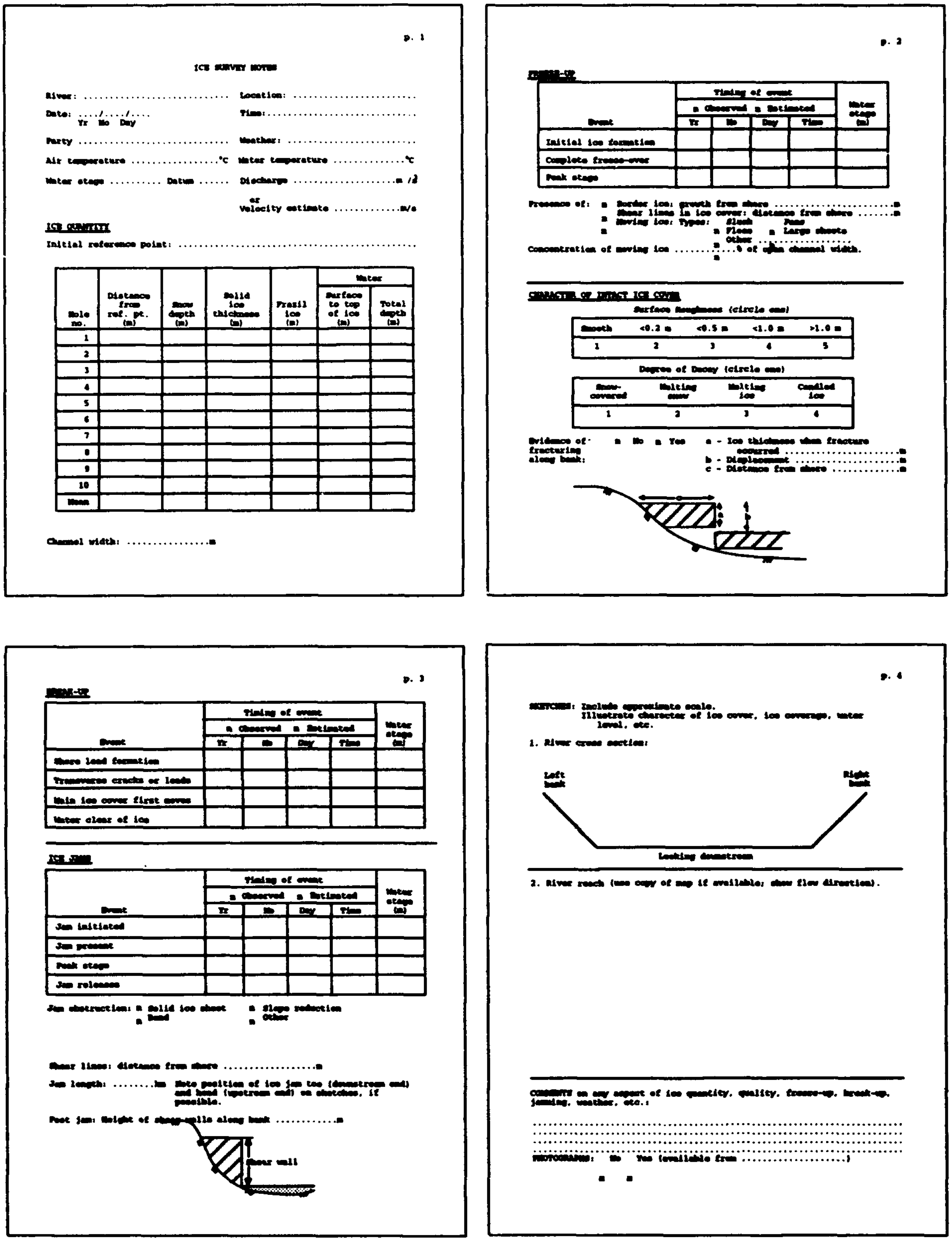
Notes: Dec 3, 1991 Frazil Ice Jam. Holes 4 & 5; soundings hit something hard. RP Elevation from FEMA FIS HEC-2 model from Minnesota DNR.



Program: @(#) icepix.c Ver 2.0 21FEB92 FE Systems

USAED-St. Paul

Figure 14. A field data collection form developed by Pomerleau (1992a, b). A blank version may be useful in collecting data efficiently.



p. 1

ICE SURVEY NOTES

River: .... Location: ....

Date: ..../..../.... (Yr Mo Day)   Time: ....

Party .... Weather: ....

Air temperature ....°C Water temperature ....°C

Water stage .... Datum ...... Discharge ....m³/s

or
Velocity estimate ....m/s

ICE QUANTITY

Initial reference point: ....

Hole no.	Distance from ref. pt. (m)	Snow depth (m)	Solid ice thickness (m)	Frazil ice (m)	Water: Surface to top of ice (m)	Water: Total depth (m)
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
Mean						

Channel width: ....m

p. 2

FREEZE-UP

Event	Timing of event (☐ Observed ☐ Estimated): Yr	Mo	Day	Time	Water stage (m)
Initial ice formation					
Complete freeze-over					
Peak stage					

Presence of: ☐ Border ice: growth from shore ....m
☐ Shear lines in ice cover: distance from shore ....m
☐ Moving ice: Types: ☐ Slush ☐ Pans ☐ Floes ☐ Large sheets ☐ Other ....

Concentration of moving ice ....% of open channel width.

CHARACTER OF INTACT ICE COVER

Surface Roughness (circle one)

Smooth	<0.2 m	<0.5 m	<1.0 m	>1.0 m
1	2	3	4	5

Degree of Decay (circle one)

Snow-covered	Melting snow	Melting ice	Candled ice
1	2	3	4

Evidence of fracturing along bank: ☐ No ☐ Yes
a - Ice thickness when fracture occurred ....m
b - Displacement ....m
c - Distance from shore ....m

p. 3

BREAK-UP

Event	Timing of event (☐ Observed ☐ Estimated): Yr	Mo	Day	Time	Water stage (m)
Shore lead formation					
Transverse cracks or leads					
Main ice cover first moves					
Water clear of ice					

ICE JAMS

Event	Timing of event (☐ Observed ☐ Estimated): Yr	Mo	Day	Time	Water stage (m)
Jam initiated					
Jam present					
Peak stage					
Jam releases					

Jam obstruction: ☐ Solid ice sheet ☐ Bend ☐ Slope reduction ☐ Other

Shear lines: distance from shore ....m

Jam length: ....km Note position of ice jam toe (downstream end) and head (upstream end) on sketches, if possible.

Post jam: Height of shear walls along bank ....m

Shear wall

p. 4

SKETCHES: Include approximate scale.
Illustrate character of ice cover, ice coverage, water level, etc.

1. River cross section:

Left bank Right bank

Looking downstream

2. River reach (use copy of map if available; show flow direction).

COMMENTS on any aspect of ice quantity, quality, freeze-up, break-up, jamming, weather, etc.:

....
....
....

PHOTOGRAPHS: ☐ No ☐ Yes (available from ....)

Figure 15. Alternative, more detailed, ice jam data collection form (after Beltaos et al. 1990).

or combination jam. Examination of core samples (Figure 16) will also indicate the predominant ice type. Thin sections of ice cores examined using polarized light will reveal the crystal structure of the ice. Ice that formed and thickened as a result of thermal processes is characterized by long, slender, vertical crystals, while snow ice and frazil ice appear as tiny particles. Snow ice and frazil ice may be distinguished by visual observations of the core and its surrounding ice cover. Specialized facilities are required for ice core analysis, so this type of analysis is relatively uncommon outside of research. Ice core sample extractions are discussed in greater detail under *Ice Thickness*, below.

Location and extent of jam

Identifying the location of the downstream end of the ice jam is extremely useful in establishing the cause of an ice jam. Similarly, it is important to locate the upstream end of an ice jam and track its progress if the ice jam continues to grow. The ends of the jam can be marked on a USGS quadrangle,

Figure 16. Thin section of an ice cover. The long slender crystals in the center represent ice growth due to heat transfer; the more chaotic ice in the lower section is frazil ice. The upper portion contains snow ice, frozen rainwater, and both frazil and thermally grown ice (Israel River, N.H.).

local town mapping, aerial photograph, flood insurance study map, or even a road map if no other map is available. Aerial surveillance is particularly useful in locating the ends of the jam if access is poor or if the jam covers a large distance (Figure 17).

Knowledge of the extent of a jam at any given time may be used to estimate the volume of ice contributing to the jam, which can be helpful in several ways. For example, a breakup ice jam is 0.8 km (0.5 mi) long with open water in the previously ice-covered reach between the upstream end of the jam and the toe of a dam located 2.4 km (1.5 mi) upstream. Therefore, 3.2 km (2 mi) of river ice is now compressed into a jam one quarter that length. Assuming a uniform channel shape, no melting, negligible ice deposited along the shore, and an ice jam porosity of 50%, a rough estimate of the jam thickness would be about eight times the initial ice thickness.

Another hypothetical case might involve a freezeup jam that has progressed 8 km (5 mi) in the past 2 days. Short-term weather forecasts call for continued cold weather for the next 3 days. Given fairly uniform channel conditions, a conservative ice jam forecast might predict that the jam would progress an additional 12 km (7.5 mi) in that time.

Upstream ice supply

Because the available upstream ice supply directly affects the potential growth of an ice jam, it should be estimated, if at all possible. In the case of a freezeup ice jam, the volume of frazil ice may be roughly estimated by knowing the length of river contributing frazil ice and the weather forecast. In general, air temperatures of −6.6°C (20°F) or above, will tend to decrease frazil production, while colder air temperatures will tend to increase it. It is important to obtain site-specific data on the rate of frazil production at different air temperatures, if possible. The presence of upstream ice covers, which may decrease frazil production or trap transported frazil, should also be identified.

For breakup jams, the volume of intact ice cover upstream from the jam, including tributary ice, should be estimated. The length and width of the ice may be estimated from maps, aerial photographs, or visual observations. The thickness of upstream ice covers may be either measured using the methods described below or estimated from the thickness of ice pieces in the jam itself. The likelihood that the upstream ice supply will contribute to the jam should be evaluated, if possible. Historical records may indicate whether the ice

Figure 17. This aerial view of a breakup ice jam shows the location of the upstream end of the jam (to the left). Flow is from left to right. The main channel of the river, which runs along the road, is blocked with ice. Ice that covered the roadway at one time hrs been plowed to either side. The presence of ice blocks in the field across the road on the left bank and overbank flow on the right bank, which occurred as a result of high water levels upstream from the jam, can be used to estimate stage (Ammonoosuc River, N.H.).

cover above a certain point breaks up and contributes to jamming.

The strength and competence of an upstream ice cover that might contribute to a breakup jam should be evaluated. Weak, relatively deteriorated ice or ice covers that contain leads or cracks generally require less force to break up than a strong, thick ice cover with no leads or cracks. If discharge is decreasing and no new precipitation or runoff is predicted, a strong ice cover may remain in place while a weaker one could still break up. If, on the other hand, continued warm weather and/or rainfall is predicted, a strong upstream ice cover poses a more serious threat than a weak one, since the breakup of a weak cover often produces smaller, weaker pieces of ice that

are more likely to break up upon impact. The stronger ice cover will require more force to break up and will also tend to cause thicker, more damaging ice jams.

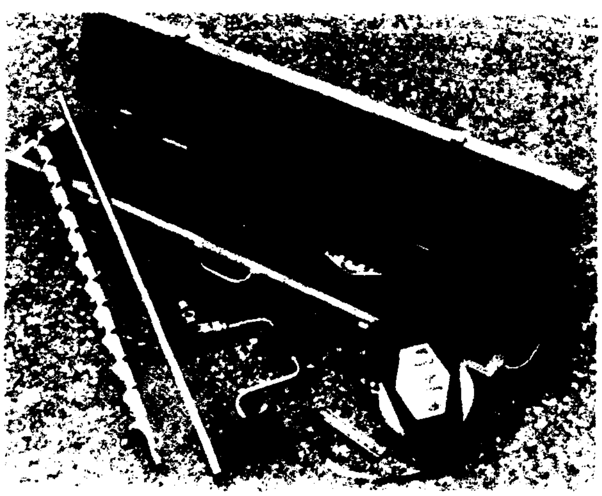
Downstream ice conditions

Observations of downstream ice conditions are particularly important in cases where ice jam removal measures are being considered. In many cases, jams are formed when ice movement is obstructed by a solid ice cover. The length, thickness, and competence of the obstructing ice cover should be evaluated before considering ice jam removal or weakening measures, because their success will depend on the concurrent weakening or removal of the obstructing ice cover.

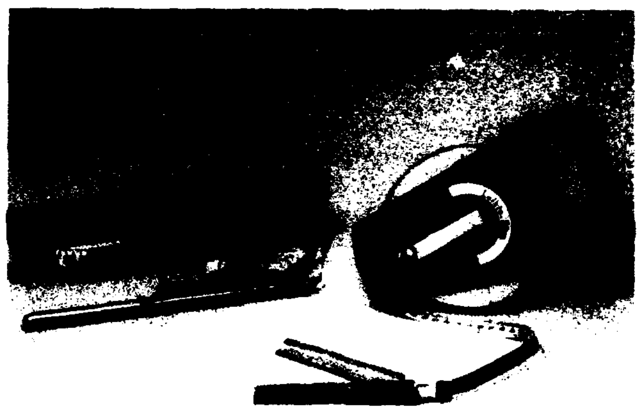
For a jam where there is no obstructing ice cover immediately downstream (at the toe), make a survey of ice conditions farther downstream. Identify the location and extent of both open-water and ice-covered areas. If the ice jam is dislodged, knowledge of the location and integrity of these downstream ice covers will be helpful in assessing whether it will rejam downstream and, if it does, whether significant flooding or damage will occur.

Ice thickness

Ice thickness is perhaps the most basic physical ice property to be measured. Thickness measurements and some estimation of the competence of the ice must be made before allowing personnel or vehicles onto an ice cover. Ice thickness may be measured either directly or indirectly. Direct measurement of ice thickness is best done using an ice thickness kit, such as the standard CRREL ice thickness kit shown in Figure 18a. The standard kit contains a two-part iron bar used to test the ice safety, an auger and bit brace for drilling holes, extension rods to increase the depth to which holes can be drilled, and a device to measure ice thickness (Figure 18b). The auger should produce a hole with a diameter of at least 5.8 cm (2.25 in.) to allow velocity measurements to be made (see *Water Velocity*, below). Wooden handles on the bit brace are preferred for working in the cold. It may also be useful to include such items as spare auger bits (carbide-tipped bits are preferred) and a folding wooden rule in the kit. The kits should be tested by each member of a field party on safe ice so that each person is familiar with the use of each item. Advice on assembling an ice thickness kit may be obtained from CRREL.



a. Standard CRREL ice thickness measuring kit. From left, auger with carbide-tipped bit, extension rod, bit brace, and ice thickness measuring device. In the box is a two-part iron bar (hollow top, solid bottom) that can be screwed together for field work and disassembled for transport.



b. Two types of devices that can be used to measure ice thickness.

Figure 18. Ice thickness measuring devices.

Direct measurement

Two types of ice thickness measuring devices are shown in Figure 18b. The general method for these devices is illustrated in Figure 19. First, a hole is augured into the ice until water is reached or until further auguring is stopped by bed material. Ice thickness is then measured using a tape measure with a hinged weight that is dropped into the hole. The distance to the bottom of the riverbed can be measured in this manner (Figure 19b), although a strong current will tend to pull the tape and make measurement difficult. Thick or dense frazil deposits may impede the weight so that it must be pushed below the deposit. When the tape is pulled back gently against the hole, the weight catches on the bottom of the ice and the ice thickness can be read on the tape (Figure 19c or d, depending on whether frazil is present or not).

Both frazil and solid ice thickness can be measured in this manner with a little practice. Frazil deposits will provide a small amount of resistance to the upward movement of the weight, while the bottom of the solid ice is much more noticeable. Some loose frazil at the bottom of the ice may be missed using this technique. If this material is important, the hole may be remeasured using only a small amount of force on the tape, or the coring auger may be used to obtain a physical sample. Very loosely deposited frazil will be difficult to measure using either method.

If the river channel is too shallow to allow the ice thickness devices to work, the thickness may be

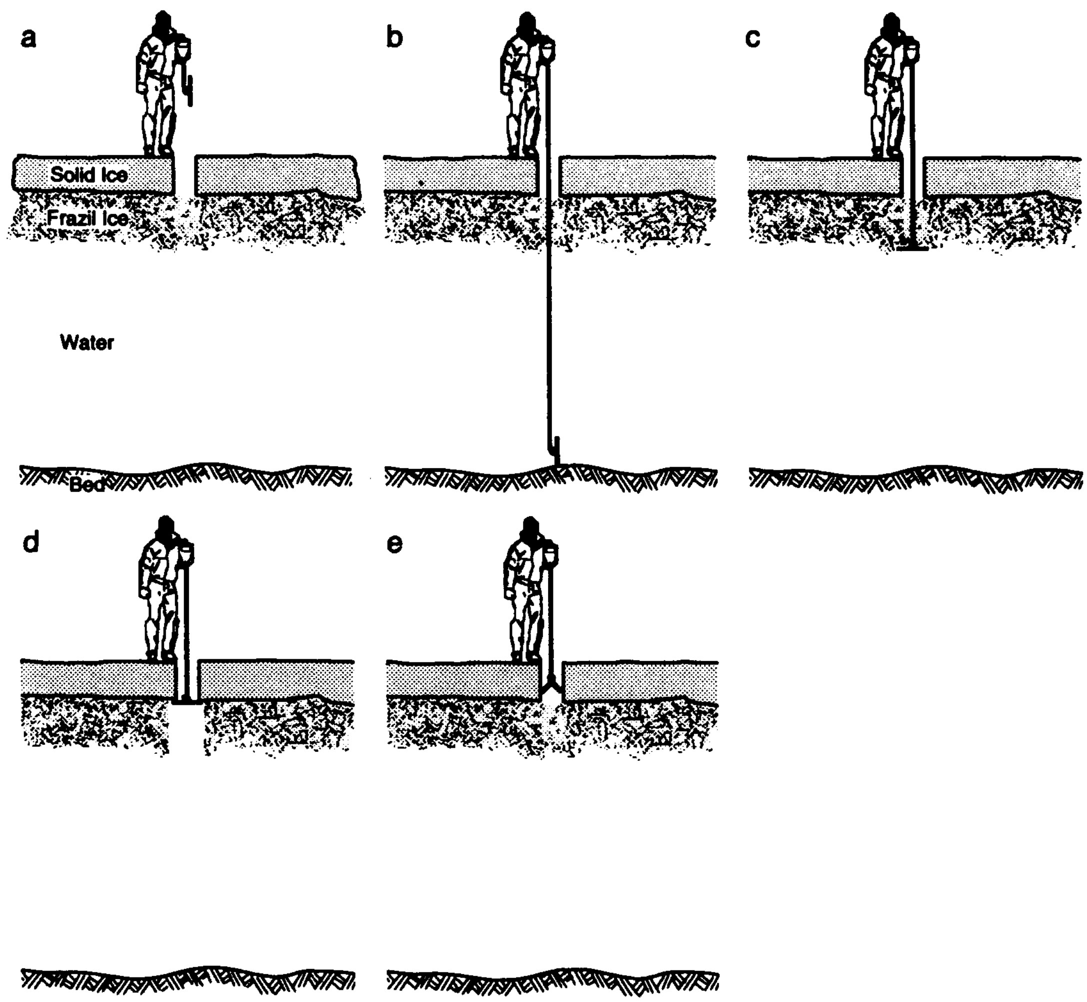


Figure 19. Measurement of ice using a device, shown on the right in Figure 19b, developed by Ueda (1983). The important measurements are: depth of bed, thickness of loose frazil ice and solid ice, and location of water level.

Figure 20. This ice core includes about 15 cm (6 in.) of snow ice at the top (left), 17.75 cm (7 in.) of relatively clear, thermal ice growth followed by about 11 cm (4.5 in.) of frazil ice and thermal ice. A loose frazil deposit is at the extreme right (Israel River, N.H.).

measured using a folding wooden rule to which a hook of some kind has been added. The rule can be used to measure the total depth to the bed, and the ice thickness can be measured by catching the hook on the underside of the ice. One researcher* uses a 3-m (10-ft) engineer rule with a curtain rod mounting bracket taped to one end.

A measure of ice thickness may also be obtained when using a coring auger to obtain ice core samples for further analysis. A 15.2-cm (6-in.)-diameter ice core sample is obtained by drilling the auger into the ice. The length of the core sample removed can then be measured. Sometimes it is possible to distinguish between frazil ice and thermally grown ice by visually examining the core (Figure 20). Thermally grown ice will appear clear, while frazil or snow ice will be cloudy. If the ice types can be differentiated, the depth of the different layers can be measured. Generally, however, it is difficult to determine the makeup of the ice without further analysis of the core. It should also be noted that relatively loose frazil may not be retrieved by the sampler.

Indirect measurement

In some cases, ice thickness estimates must be made after the ice cover is no longer in place. If ice blocks remain on the overbanks after an ice event, they may be measured soon after the event to determine the original ice cover thickness (Figure 21a). If some time has gone by, particularly when warm temperatures or rain have occurred, the thickness and character of the ice pieces may not be representative of the pieces that made up the jam. A rough estimate of ice thickness may be provided using ice thickness measurements from nearby rivers with similar geometry if no other information is available. Ice jam thickness can be estimated from the height of ice shear walls that are typically left on the banks of a river following the failure of a jam (Figure 21b).

Ice thickness may also be estimated by using a velocity probe (see *Water Velocity*, below) to locate the bottom of the ice cover. The velocity will remain zero as the probe is lowered through the ice cover, but when the bottom of the cover or frazil deposit is reached, the underlying water velocity will register on the meter. The distance between the level of the initial positive velocity and the top of the ice can then be measured to determine ice thickness. The velocity gradient just below the ice is often quite steep, so that the demarcation between flowing and still water is relatively clear (Figure 22). If not, however, it may be difficult to determine the actual bottom of the ice cover using this method. Flow can occur through unfrozen frazil deposits and fragmented ice jams, but the velocity of flow is generally quite low (except where piping occurs).

Water velocity

Flow velocity can be measured either by timing the movement of surface objects in open-water flow areas or by using a velocity probe. The general method of measurement with a velocity probe

* R.T. Pomerleau, 1993, personal communication.

a. Measure ice pieces to estimate pre-breakup thickness. Here, about 5 cm (2 in.) of snow ice overlie 10 cm (4 in.) of solid ice. More than 15 cm (6 in.) of frazil was originally deposited beneath the solid ice.

b. Ice jam thickness can be estimated from the shear walls left after ice jam failure. The composition of this breakup jam was a combination of large ice blocks cemented by frazil ice (Ottauquechee River, Vt.).

Figure 21. Ice pieces left on overbanks and shear walls left behind can provide an estimate of ice jam thickness after jam failure

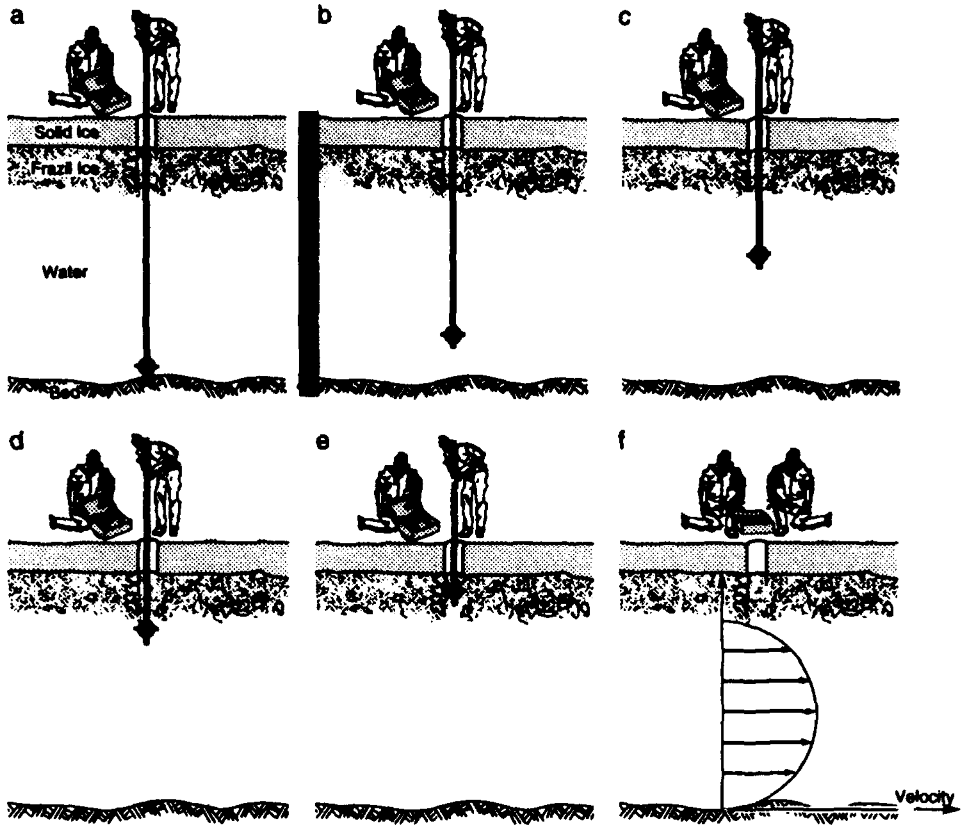


Figure 22. A velocity probe can be used to locate the depth to the bed and measure the thickness of a frazil deposit as well as to obtain information on water velocity.

is shown in Figure 22. A hole large enough to fit the probe (at least 5.8 cm or 2.25 in.) is augured into the ice. The probe is then inserted and lowered until it meets refusal. The depth below the top of the ice and the measured water velocity are recorded. The probe is then raised and the depth and velocity are recorded at intervals until the velocity drops to zero (Figures 22b through 22e). The result is a velocity profile such as that shown in Figure 22f. Velocity measured in a number of holes across a river will provide riverbed geometry and ice profile information as well as velocity profiles, as shown in Figure 23 and 24.

When taking velocity measurements, it is best to obtain information needed to develop as complete a profile as possible. The depth and magnitude of maximum velocity should be recorded. If you wish to calculate mean velocities or discharges from the data, velocity measurements should be collected in a manner consistent with methods described by Buchanan and Somers (1969), Rantz et al. (1982), and the Bureau of Reclamation (1984). In general, they suggest taking velocity measurements at 0.2 and 0.8 times the effective depth (the depth beneath the ice cover) when the effective depth is greater than 76 cm (30 in.), and at 0.6 times the effective depth if it is less than 76 cm. (These measurements should be taken in addition to other measurements made to develop a full-depth velocity profile.)

There are a number of types of instruments available for making velocity measurements. However, instrument probes that have moving parts often freeze up, either from ice adhesion beneath the surface or from exposure to cold air after the wet probe is removed from the water, and the quality of the measurements is diminished. These types of instruments may be used with care, which usually involves warming and drying the probe between borehole locations. Electromagnetic velocity probes (Figure 25) are not affected by freezing since they have no moving parts, and any ice accumulations on the probe can be easily removed. Buchanan and Somers (1969) and Rantz et

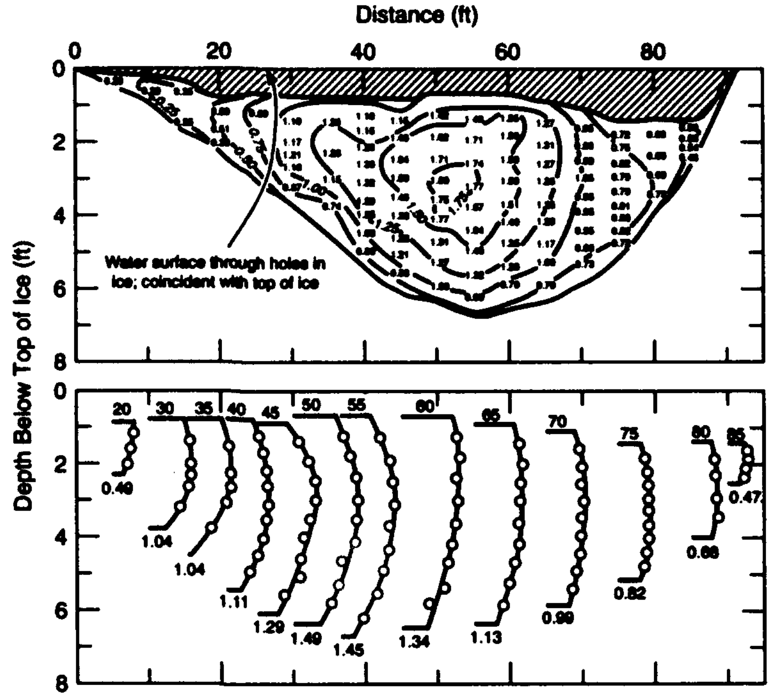


Figure 23. Velocity profile beneath an ice cover. A velocity probe can be used to determine the level of the bottom of the ice cover, because the water velocity quickly increases above zero at this location. This diagram shows the distribution of horizontal and vertical velocities under a complete ice cover (Cannon River at Welch, Minn., after Hoyt 1913).

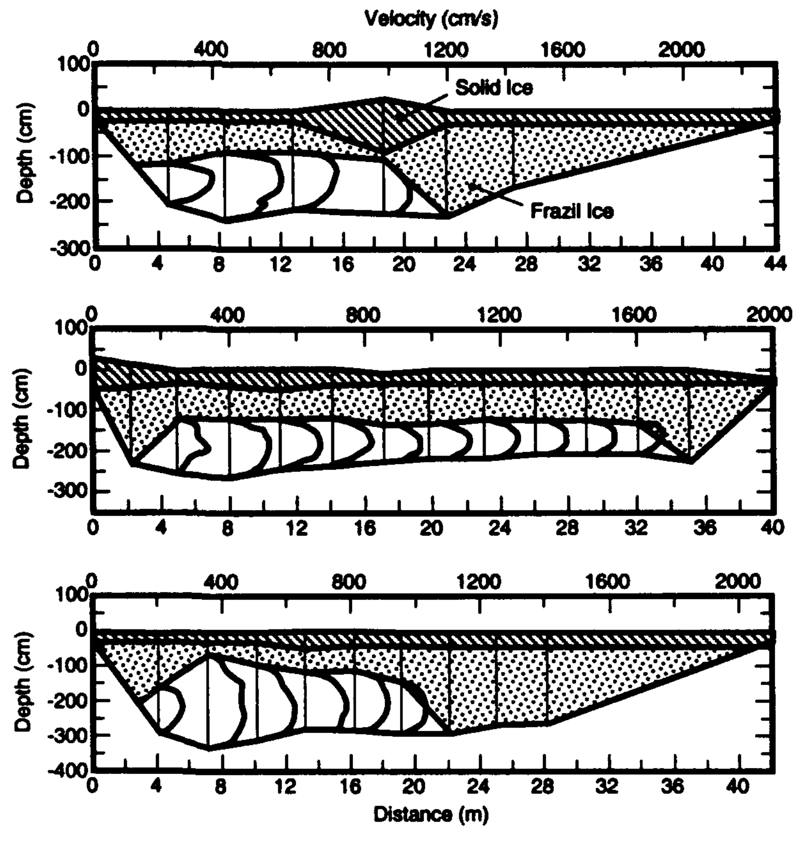
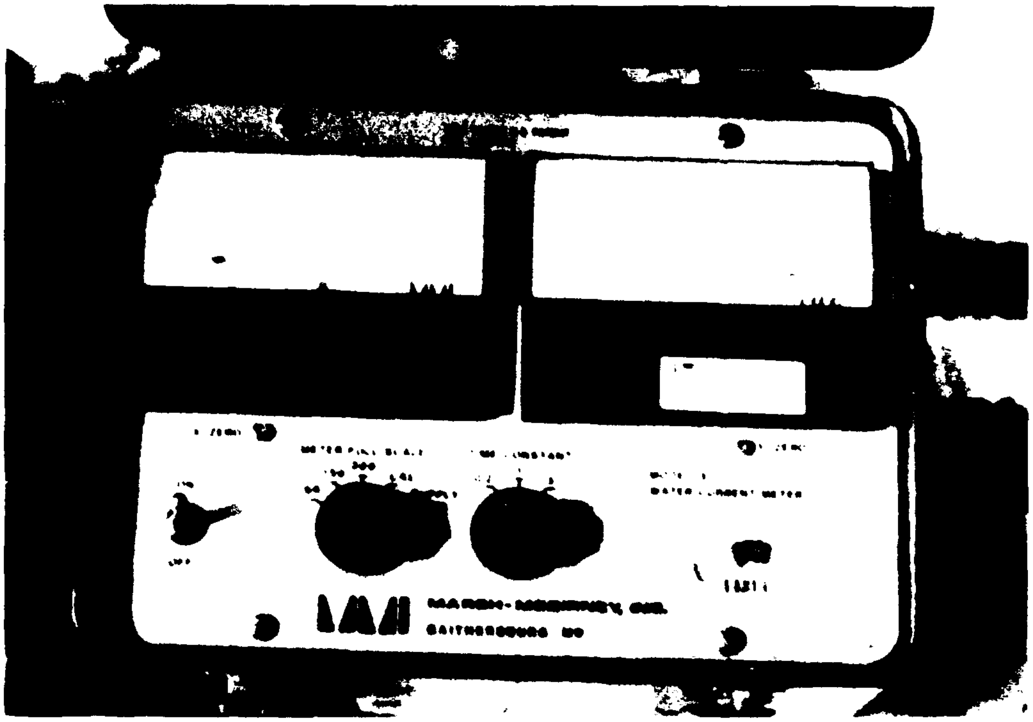


Figure 24. A series of velocity measurements across a river cross section can also provide :iverbed and ice thickness profiles (Salmon River, Idaho).



a. Velocity can be measured in two directions.

b. The sensor has no moving parts to freeze when removed from the water.

Figure 25. Electromagnetic velocity probes can be used to measure velocity profiles under ice.

Figure 26. Photographic records can be useful in determining ice jam characteristics. Here ice debris can be seen on the low steel of the bridge, an indication of the ice jam stage. The ice pieces left on the bank indicate that this was a breakup jam that also contained frazil ice (Israel River, N.H.).

al. (1982) discuss methods of obtaining velocity measurements under ice using other types of probes.

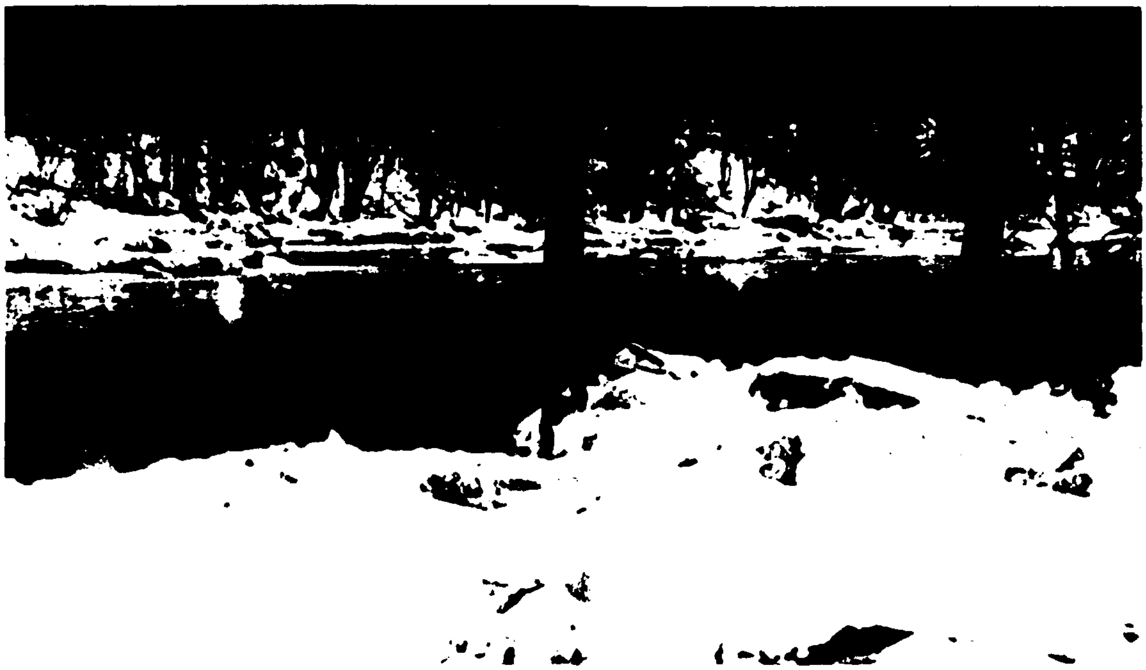
When adequate velocity-measuring instruments are not available, or when the condition of the ice prohibits access, velocity measurements may be made by timing the movement of objects on the water surface. Usually, a distance is measured or paced out along the shoreline. Then, the time that small objects require to traverse this distance is measured. Small objects are preferred since they will tend to move at nearly the same speed as the water, but ice floes or pans will suffice. Usually, several measurements are made and then averaged.

Water stage

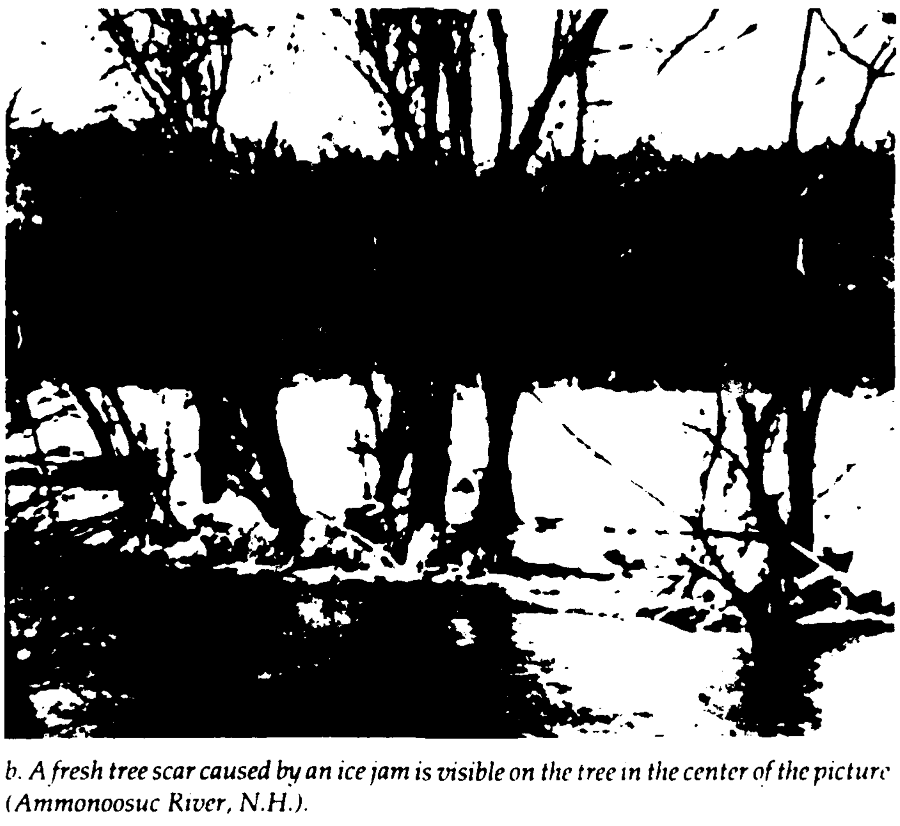
Water stage measurements may be obtained from a variety of sources. USACE (1991) presents a discussion of several methods of determining water stage after an event. The reliability of stage data will vary with the method used to obtain the data and how long after an event the data is collected. High-water marks set during an ice jam event and surveyed later provide accurate, relatively low-cost stage records. USGS water-level gauge stage records may be used, keeping in mind that they may be ice-affected, as discussed previously. Indirect methods of measuring stage include photographic records, which can be particularly useful in estimating stage during and after an event (Figure 26). Tree scars made by ice or other ice damage can be used to estimate water levels (Figure 27). Collars of ice often form around trees or other objects at or near the maximum water level if the event occurs during subfreezing temperatures. The elevation of these ice collars can be used to estimate stage or ice thickness at a particular location (Figure 28). The presence and location of ice blocks on the overbanks after an ice jam event also indicate past stages, but with less accuracy as they may lie above or below the actual water level (Figure 29).

Ice roughness

The roughness of the underside of an ice cover has a direct impact on the hydraulic conditions beneath the ice jam. Very rough ice covers in shallow waters can result in significant erosion of the bed or banks. Rougher ice covers will also decrease flow capacity because of increased friction. Ice roughness is difficult to quantify, but one method generally used is to assume that the roughness of the ice surface is indicative of the roughness of the ice bottom (Figure 30). The height of roughness elements above the surface can be estimated from visual observations or from photographs. Ice roughness may also be calculated knowing the discharge, bed roughness, and water slope (Carey 1968a, b). Water slope can be measured by



a. Ice blocks piled up around tree on shore. Ice pieces carried along in ice jams can scar trees, leaving evidence of the ice jam stage. An old scar made by ice is visible on this tree (Israel River, N.H.).



b. A fresh tree scar caused by an ice jam is visible on the tree in the center of the picture (Ammonoosuc River, N.H.).

Figure 27. Tree scars and other ice damage can be used to estimate water levels.

Figure 28. The ice collars formed at the high-water level are still evident following failure of the jam and a minor snowfall (Indian River, N.H.).

Figure 29. Ice pieces left on the overbanks can indirectly indicate water levels and areas of flooding. Here, the pre-breakup cover was composed of snow ice, frazil ice, and thermally grown ice up to 60 cm (2 ft) thick (Waits River, Vt.).

Figure 30. The roughness of the surface of an ice jam is a good estimate of the roughness of its underside. This very rough breakup jam resulted in the stage of record, well above the stages associated with two hurricane events, even though the ice jam discharge was only 1/6 of the hurricane discharges (Delaware River, N.Y.).

surveying the water levels at boreholes in the ice cover. The discharge can be estimated using velocity measurements and geometry information, or it may be transposed from a nearby, non-ice-affected USGS gauge.

Air and water temperature

Air temperatures may be obtained from a variety of sources, including the National Weather Service, radio stations, and local observers. During an ice jam event, the actual and forecast air temperatures in the entire watershed should be monitored and recorded. Air temperature forecasts can indicate the stability of the jam in case measurements are planned from the surface of the ice, and they can also be used to estimate the progress or decay of the jam.

Freezeup jams are usually associated with cold air temperatures and increased frazil ice production. If the air temperature remains cold after a freezeup jam forms, and continued cold is forecast, then the jam is likely to progress. If discharge remains fairly steady, the jam is also likely to become more stable as the frazil making up the jam freezes together. If warm air temperatures occur after a freezeup jam forms, however, the jam progression will slow or stop, and the jam may begin to erode. Frazil ice jams are often unstable in warm conditions. Monitoring water temperatures can also be useful in a freezeup jam situation. If water temperatures are more than half a degree above freezing, the water may erode the ice jam as frazil ice production will have ceased.

Breakup jams often form during relatively warmer air temperatures as a result of increases in discharge due to snowmelt and/or precipitation. A forecast of colder air temperatures following the formation of a breakup jam might cause the ice jam to freeze in place. Often, runoff decreases as the temperature drops. On the other hand, warm air temperatures following the formation of a breakup ice jam might indicate the possibility of continuing or increased runoff. The warm air temperatures may decrease the strength of the ice to some degree through surface melting. Warm water temperatures will also tend to erode a breakup ice jam.

Water temperatures are more difficult to obtain than air temperatures. Some USGS gauges moni-

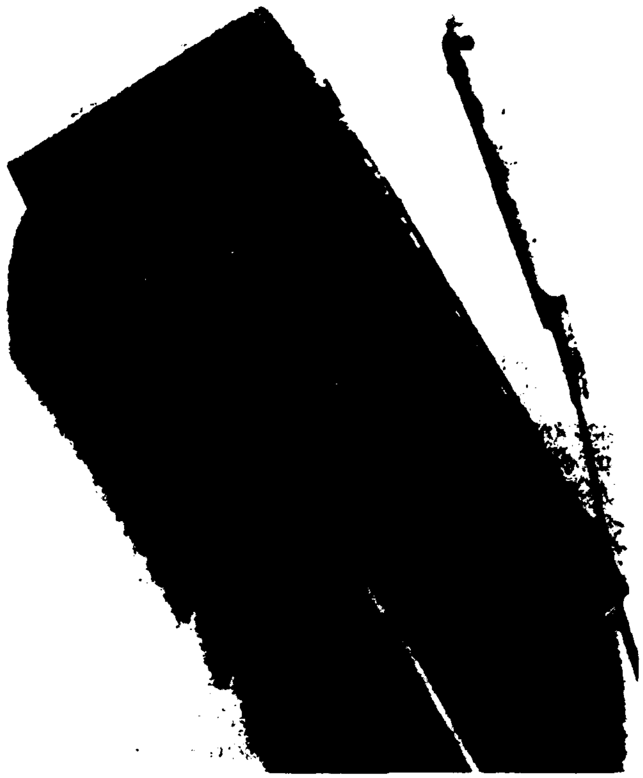


Figure 31. Glass-bead thermistor.

tor water temperatures in addition to stage and discharge. But often the sensitivity of the instruments prevents them from identifying either supercooled water or water slightly above freezing, so that water temperatures of −0.01°C (31.9°F) (supercooled) and 0.4°C (32.7°F) (warm enough to melt ice) might both register as 0°C (32°F).

Water temperatures can be measured locally using a thermometer if temperatures above freezing are to be monitored. Supercooling is more difficult to measure accurately. Glass-bead thermistors monitored with a digital multimeter, such as those used by CRREL researchers, produce the best results (Figure 31). However, if such devices are lacking, one may assume that supercooling is present at some point if frazil ice floes are present in the river. Large concentrations of frazil ice indicate that a larger percentage of the river's length has supercooled water temperatures. On the other hand, the presence of a small amount of frazil in the river can indicate several things: that a small portion of the river is producing frazil ice, that air temperatures are not cold enough to produce supercooled water at many locations, or that the frazil being produced upstream is being captured in an upstream ice jam.

SUMMARY

Relevant data must be collected in order to understand and alleviate ice jam problems. The development of an ice jam data collection program must consider the objectives of the program as well as the constraints upon it. The magnitude and extent of an ice jam data collection program depends in large part on the integration of objectives and constraints.

Background data collection involves a review of all existing information regarding the ice jam site, including ice data, mapping, technical reports, flood insurance studies, hydrologic and meteorological records, newspaper reports, and anecdotal records. The results of background data collection can be extremely useful in identifying the constraints on field data collection as well as the type of ice jam, potential damages, and possible mitigation measures to be used.

Preparation of a safety hazard analysis is vital in developing an ice jam field data collection program.

Field data collection efforts are guided by the intended result of the study and the amount of time available: more detailed field work is associated with the design of an ice control structure than when data is needed immediately to deal with an emergency situation. The types and quantity of field data desired under optimum conditions should be determined. These objectives are then modified by the constraints that have been identified. Alternative methods or types of data should be developed, because safety and site conditions often may further modify planned data collection efforts.

A well-designed ice jam data collection program will provide the flexibility necessary to deal with changing field conditions. Early identification of safety hazards and other constraints will allow for safe, efficient collection of high-quality data that can then be used to achieve the result intended.

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13. ABSTRACT (*Maximum 200 words*)

Ice jam data collection is necessary to gain information on ice jam events, which may occur rarely and are often short-lived, but can at the same time cause large damages. An ice jam data collection program involves field data collection, review of existing hydrologic, hydraulic, meteorological, and ice records, and a search of historical records that may pertain to ice events. This report describes the development of an ice jam data collection program, the types of information to be collected, and techniques used in field ice jam data collection.

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